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Lithospheric weakening during "retroforeland" basin formation: Tectonic evolution of the central South Alpine foredeep

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Abstract. Beginning with the Late Cretaceous, convergence between Europe and Adria caused the southward subduction of the European plate beneath Adria. Contractional movements at high crustal levels were partly accommodated by southward thrusting (Southern Alps) causing flexure of the loaded Adriatic plate and the formation of the Late Cretaceous to Late Miocene South Alpine foredeep. With respect to the Alpine subduction system, the South Alpine foredeep is a retroforeland basin. In the Late Paleogene, dip values of the base foredeep varied between 3° and 5°. The shallower dips were found along profiles crossing domains which had undergone extension during previous Late Triassic to Middle Jurassic rifting. With ongoing convergence, the base foredeep along the entire basin steepened and dip values in the Tortonian are of about 7°-8°. The increase in dip goes hand in hand with an increase in the curvature of the loaded plate. This suggests a progressive weakening of the flexed plate. Modeled effective elastic thickness (*Te*) values derived from the analysis of plate curvatures decrease from 15-20 km in the Late Paleogene to <5 km in the Tortonian. Preconvergence values obtained from modeling studies were even higher, in the 24-27 km range. A practically complete decoupling of the upper/middle crust from its mantle substratum enabled the increase in curvature of the hinge zone. The progressive weakening of the South Alpine lithosphere around the bulge zone is correlated with the its "upper plate" position with respect to the Alpine subduction system.

1. Introduction

As a response to loading caused by thrust sheets emplacement, the lithosphere flexes and allows thereby the formation of a foredeep or foreland basin [*Price*, 1973; *Beaumont*, 1981]. The basin geometry is strongly controlled by the mechanical properties of the loaded plate which are often laterally variable as a consequence of previous tectonic events such as rifting and passive margin formation [*e.g., Zoetemeijer et al.*, 1990; *van der Beek and Cloetingh*, 1992; *Waschbusch and Royden*, 1992; *Millan et al.* 1995]. The basin shape can change through time as a consequence of the introduction into the system of mechanically different lithospheric segments [e.g., *Stockmal et al.*, 1986] but also as a result of in situ processes causing changes affecting the loaded plate itself. These have attracted little attention hitherto.

Two different foreland basins usually develop in collisional settings [*Dickinson*, 1974]: one on the subducting plate (proforeland of *Johnson and Beaumont* [1995]) and one on the overriding plate in front of the retrowedge (retroforeland of *Johnson and Beaumont* [1995]). In proforeland basins, a steady state is expected, and lithospheric segments initially in a bulge and back-bulge position are progressively incorporated into the basin and buried by younger sediments [e.g., *DeCelles and Giles*, 1996]. Changes in time of the shape of proforeland basins mainly reflect the lateral introduction into the system of mechanically variable lithospheric segments. On the other side, the upper plate, which sustains retroforeland basins, can hardly be subducted (for an alternative view see *Tao and O'Connell* [1992]). Consequently, the lithosphere cannot move through the system and changes in basins geometry should mainly be associated with in situ modifications of the loaded plate mechanics. While a number of studies have been published on the proforeland basins [*Stockmal et al.*, 1986; *Sinclair and Allen*, 1992] much less is known about the retroforeland ones (see, however, *Stern et al.* [1992], *Holt and Stern* [1994], and *Johnson and Beaumont* [1995]) despite their apparent importance.

Lithospheric mechanical properties are usually described by means of the effective elastic thickness (*Te*). As pointed out by *Burov and Diament* [1995], the *Te* is, in fact, mostly used as a "black box" which merely relates the calculated flexure of a thin elastic plate to the observed deflection irrespective of the real properties of the plate and of the distribution of stresses and strain. Together with recent attempts to give a more physical description of the flexure process [*Burov and Diament*, 1992, 1995; *Ranalli*, 1994] and how this changes through time [e.g., *Willett et al.*, 1985; *Rutter and Brodie*, 1992; *Kruse and Royden*, 1994], there is a strong need for well documented case studies against which the models can be tested. This is particularly true for the continental lithosphere, the strength of which is profoundly influenced but not related in a simple way to parameters such as age, tectonic setting, composition, and curvature [*Watts*, 1992; *Burov and Diament*, 1995; *Cloetingh and Burov*, 1996].

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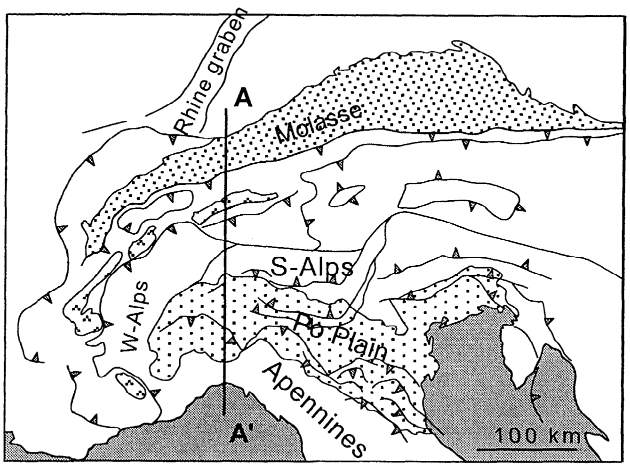

Figure 1. Tectonic sketch of the Alpine-Apennine region. Thrusting is mainly south vergent in the Southern Alps and north vergent in the Apennines. The solid line marks the trace of the profile of Figure 2.

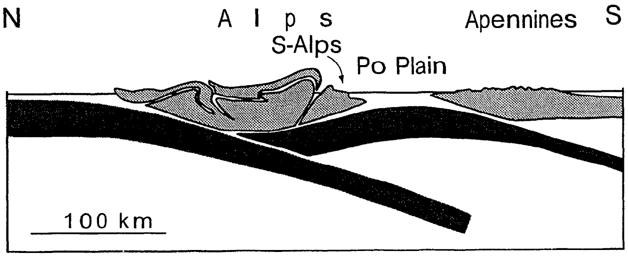

Figure 2. Schematic lithospheric profile across the Alpine-Apenninic system (simplified from *Giese et al.* [1992]).

The South Alpine foredeep and especially its central part (Figure 1) represents a well-constrained case study to document the evolution through time of such retroforeland basins. After having undergone Late Triassic to Middle Jurassic continental rifting and subsequent drifting, the northern part of the Adriatic plate was shortened in association with convergent movements between Europe and Africa. The foredeep developed on top of a section of the Mesozoic passive margin of the Adriatic plate. Convergence at depth was accommodated by the southward subduction of Europe beneath Africa [*e.g., Bernoulli et al.*, 1990; *Pfiffner et al.*, 1990]. The Adriatic plate wedges in the European plate possibly at middle to lower crustal levels and can be followed toward the north well under the Central Alps (Figure 2) [*Pfiffner*, 1992; *Giese et al.*, 1992]. Shortening at higher crustal levels was accommodated by both northward and southward thrusting. The north vergent load formed the proforeland, Molasse basin of Switzerland, Austria, and Germany [*e.g., Homewood et al.*, 1986; *Pfiffner*, 1986]. The south vergent one, the South Alpine fold-and-thrust belt, formed the South Alpine foredeep (retroforeland basin) part of which is presently buried beneath the Upper Miocene to Recent postorogenic clastics of the Po Plain. The South Alpine foredeep developed on the overriding plate and is therefore a retroforeland basin. To the south, the Adriatic plate was loaded and flexed by the north to NE vergent Apenninic fold-and-thrust belt [*e.g., Giese et al.*, 1992] in front of which a foreland basin developed (Figure 2) [*e.g., Ricci Lucchi*, 1986].

In this paper, we use mainly seismic- and well-derived data to constrain the tectonic evolution of the South Alpine foredeep basin. Applying simple geometrical techniques, we derive the curvature of the loaded plate during and at the end of thrusting. Models correlating the stresses generated in a curved plate, and yield strength envelopes allow for a translation of curvatures into *Te* values. These are then compared with estimates derived for the preloading configuration thereby enabling a complete model description of the mechanical changes suffered by the loaded plate from the onset to the end of contraction. These changes are then interpreted in the frame of the large-scale subduction processes affecting the Alps.

2. Tectonosedimentary Evolution of the South Alpine Foredeep

Shortening in the South Alpine upper crust started prior to Middle Eocene times [*Brack*, 1981] but most likely began already in the Late Cretaceous [*Doglioni and Bosellini*, 1989] and lasted until the Messinian [*Pieri and Groppi*, 1981]. The direction of shortening changed through time but typically was at high angle to the Mesozoic direction of extension [*e.g., Castellarin et al.*, 1992]. Total shortening estimates vary between 80-110 km [*Schönborn*, 1992] and 55-65 km [*Picotti et al.*, 1995]. A foredeep basin developed in front of the thrust belt allowing for the deposition of several kilometers of clastic sediments (Figures 2 and 3).

During the Late Cretaceous, orogen-derived sediments were deposited in the Lombardian basin as a clastic system of deep-sea mainly terrigenous turbidites [*e.g., Bernoulli and Winkler*, 1990 and references therein; *Bersezio*, 1993]. The locally up to 2 km thick interval is essentially of Turonian-Campanian age and is capped by a Late Cretaceous to early Eocene fine-grained hemipelagic succession ("Scaglia") punctuated by coarser episodes. The Middle Eocene to Early Oligocene evolution of the South Alpine foredeep is poorly known because of the scarcity of outcrops. Lower to Middle Eocene siliciclastic to carbonate turbidites have been recently recognized at the eastern parts of the Lombardian foredeep. A Late Eocene bioclastic deep water fan (Ternate Formation) developed west of Lake Como [*Bernoulli et al.*, 1987], whereas hemipelagic marls (Gallare Formation) were deposited in most of the South Alpine foredeep [*e.g., Mattavelli and Marcucci*, 1992].

From the Early Oligocene to the Middle Miocene, an up to 3 km thick clastic sequence was deposited in the internal parts of the foredeep basin. The mud drape of the external ramp in the Po Plain subsurface is formed by the Gallare marls [*Dondi and D'Andrea*, 1986]. Mainly on the basis of field data, the succession has been subdivided in four major sequences [*Gelati et al.*, 1988, 1991; *Bernoulli et al.*, 1989]. The first one (Chiasso Formation; Late Rupelian-Early Chattian) is made up by a 170 m thick interval of siltstones and mudstones with rare coarse-grained intercalations deposited on a base-of-slope setting in an upper bathyal (600-1200 m) condition. The Como Conglomerate forms the second depositional sequence and represents the base of the Gonfolite Lombarda group. It consists of a 1500 m thick succession of deep water conglomerates of Late Chattian-Early Burdigalian age, passing laterally into thin-bedded turbidites and mudstones. The coarse-grained portion was deposited in a submarine canyon system cut into the Chiasso Formation and

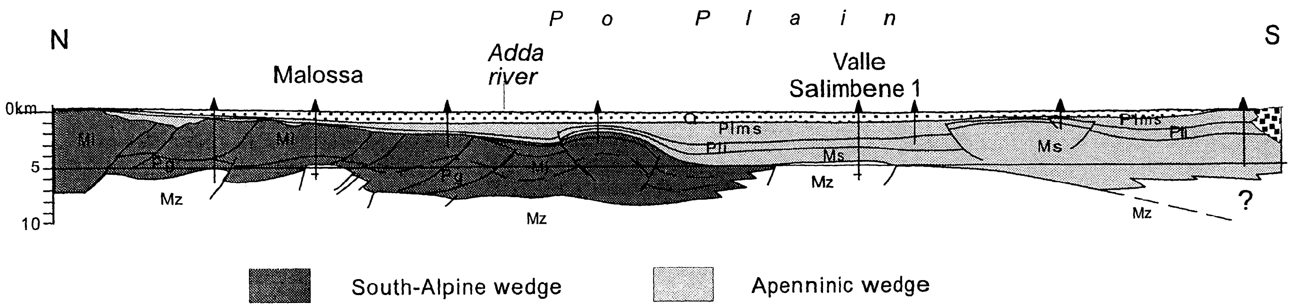

Figure 3. Interpreted seismic section along profile C [from *Pieri and Groppi,* 1981] (for location see Figure 4). Note the presence of two important Mesozoic highs: at Malossa and Valle Salimbene 1. The first one was buried beneath the Alpine wedge, the second one, located in a more favorable position, acted as a site of minimum sedimentation during Paleogene to Miocene times.
Abbreviations are as follows: Mz, Mesozoic; Pg, Paleogene; Mi, Lower Miocene; Ms, Upper Miocene; Pli, Lower Pliocene; Plms, Middle to Upper Pliocene; and Q, Quaternary.

grading laterally to interchannel and levee facies. The distal equivalents of the Como Conglomerate are thick-bedded sandstones rapidly prograding over the hemipelagic drape of the basin plain. During Aquitanian to Early Burdigalian times, these sandstone lobes onlapped the Como Conglomerate ending the depositional sequence. The third depositional sequence, defined at the base by an erosional unconformity, is formed by the 1000 m thick Lucino conglomerates of Late Burdigalian - Early Miocene (?) age [*Gelati et al.,* 1988; *Bernoulli et al.,* 1989]. This deep water fan of conglomerates and pebbly sandstones grades laterally and upward into mudstones and thinner-bedded turbidites. The Lucino conglomerate is unconformably overlain by a fourth sequence of Middle Miocene age consisting of 150-200 m of coarse-grained deposits of a channel-levee complex passing laterally into mudstones. The entry points of the drainage system feeding the foreland basin were controlled by the partly inverted main Mesozoic normal faults [*Gandolfi et al.,* 1983; *Rossi and Rogledi,* 1988]. Water depths in the foredeep were laterally variable. A morphologically depressed area was present from Langhian to Tortonian times in the southern continuation on the Lombardian basin and was flanked by two areas with much shallower even zero water depths [*Dondi and D'Andrea,* 1986]. The depressed area enabled the transport of Alpine-derived clastics into the Marnoso-Arenacea basin foredeep of the Apennines [*Ricci Lucchi,* 1986].

In the Messinian, after the end of thrusting in the central Southern Alps, a new sedimentary cycle began which continued until the Quaternary. The geometry of the sedimentary bodies deposited during this cycle is mainly controlled by the rapid northward movement of the Apenninic fold-and-thrust belt and of the associated foredeep (Figure 3). As a consequence, the southern part of the South Alpine foredeep was incorporated in the Apennines foreland basin, and the coastal onlap moved toward the north, and the ingression reached its maximum penetration in the chain during the Early Pliocene.

3. Changing Geometry of the Basin

To discuss the geometric evolution of the South Alpine foredeep, we present two sets of profiles across the basin (Figure 4 for location) showing the position of the base foredeep [*Royden,* 1988] at the end of the Paleogene and at the Tortonian. The selected profiles run roughly in N-S direction crossing

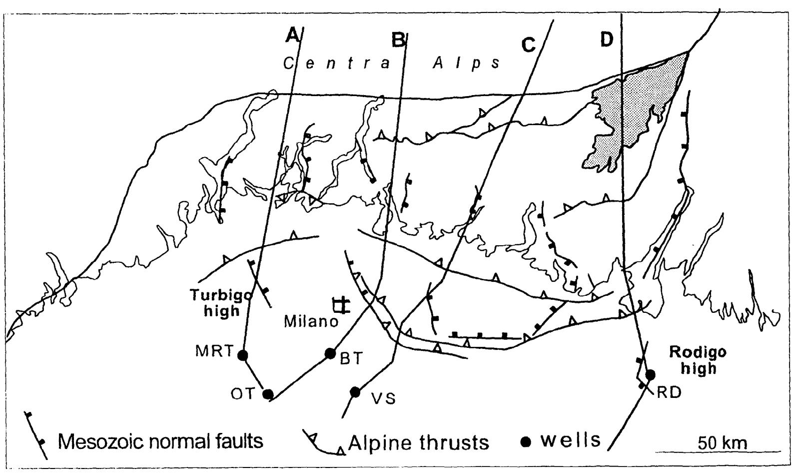

Figure 4. Main Alpine structural elements. Solid lines indicate the profiles shown in Figures 5 and 6. Wells are marked as follows: MRT, Mortara; OT, Ottabiano; BT, Battuda; VS, Valle Salimbene 1; and RD, Rodigo.

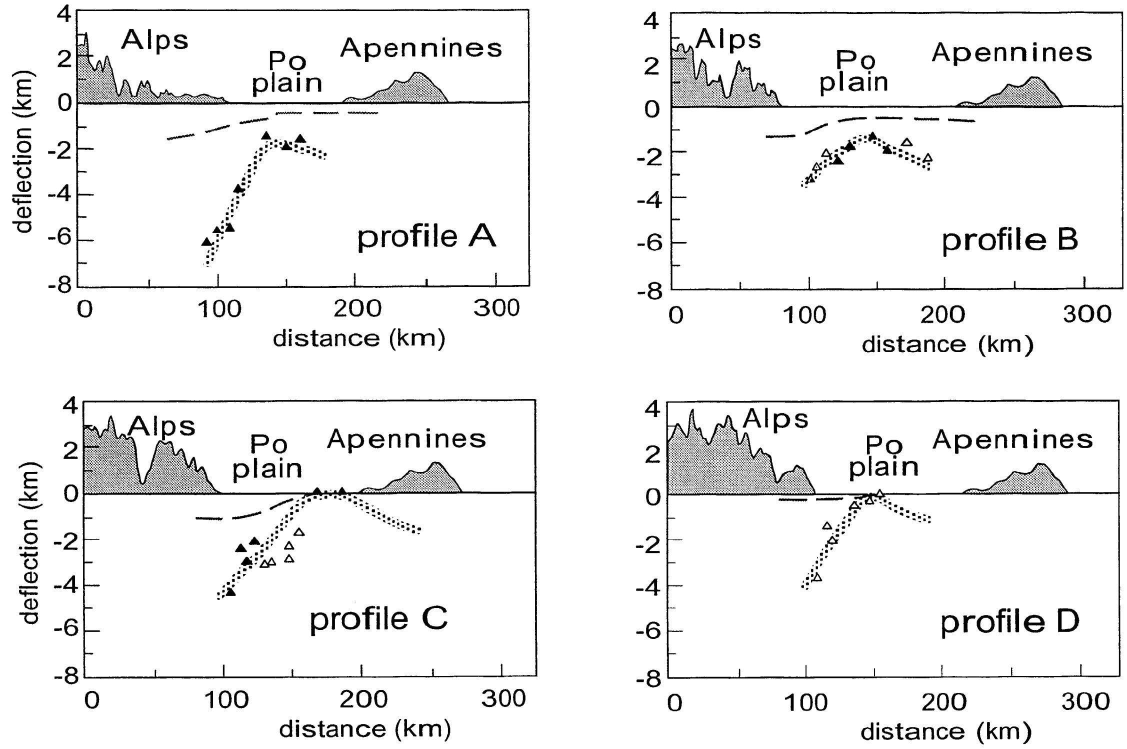

Figure 5. Base foredeep at the Late Paleogene along the four profiles shown in Figure 4. Solid and open triangles show well-constrained and less well-constrained thicknesses, respectively. The dashed lines give the paleobathymetric profiles adopted (from *Bernoulli et al.* [1987], *Gelati et al.* [1988, 1991], *Dalla et al.* [1992], and *F. Barbieri* (unpublished data, 1995)). The stippled line is a qualitative envelope of the data points. The topographic profiles of Alps and Apennines shown in the graphs are meant only as geographic reference to the present-day situation.

domains with different mechanical properties acquired during Mesozoic rifting and drifting (see below). The base foredeep is taken at the transition between the deep water carbonates (Maiolica Formation) and the terrigenous turbidites of the Upper Cretaceous Scaglia Formation. This is the horizon imaged in seismic profiles; the Mesozoic-Tertiary boundary falls within the Scaglia Formation and can be only stratigraphically defined. The Tortonian marks the end of shortening in the central and western Southern Alps. The Messinian to Present evolution of the central Po Plain is mostly posttectonic with respect to South Alpine thrusting and is beyond the topic of this paper. We mainly focus our attention to the central-western Southern Alps: in the westernmost termination of the Po Plain, the interfering Apenninic and Alpine chains make a detailed analysis extremely complex [*e.g., Piana and Polino*, 1995]. The evolution of the eastern part of the South Alpine foredeep is quite different because it is affected by the load caused by the SW vergent Dinaric chain [*e.g., Massari*, 1990].

The geometry of the foreland basin along the profiles has been derived from seismic sections [*Pieri and Groppi*, 1981] integrated with the data presented by *Dondi and D'Andrea* [1986] and with our own observations along the basin margins. The depth points given in the profiles of Figures 5, 6, and 7 are taken in places with the least possible degree of tectonic complications. Measured thicknesses have been delithified (procedure according to *Bond and Kominz* [1984]) and added to the paleobathymetric profile shown in Figures 5 and 6 to obtain the position of the base foredeep. Error margins in the final figures derive from 1) the various porosity curves adopted for decompaction and 2) uncertainties in the microfossils-based paleobathymetric estimates. In total, error margins are less than 500 m.

3.1. The Late Paleogene

The Paleogene foredeep basin (Figure 5) accommodated more than 4000 m of sediments thinning toward the south. The geometry of the basin shows noteworthy lateral variations. The dip of the base foredeep (top Mesozoic) changed along the strike of the basin (Figures 5 and 6) and is of <3.5° in profiles B and C and >5.5° in profiles A and D (see Table 1 for numerical values). This systematic difference suggest that the central domains of the investigated areas were stronger than the lateral ones.

The map-view position of the bulge associated with the Paleogene foredeep is well constrained in most of the available profiles. In profile A, it is located in correspondence to the area between the Mortara and Ottabiano wells (Figure 4) [*Pieri and Groppi*, 1981]. The bulge is particularly well expressed in profiles B and C (Figures 3 and 4) where it corresponds to the Battuda 1 and Valle Salimbene 1, wells respectively. In this latter drilling, Upper Miocene sediments were found to lie directly on top of Mesozoic beds. Along profile D, the position of minimum sedimentation is constrained by the Rodigo 1 well

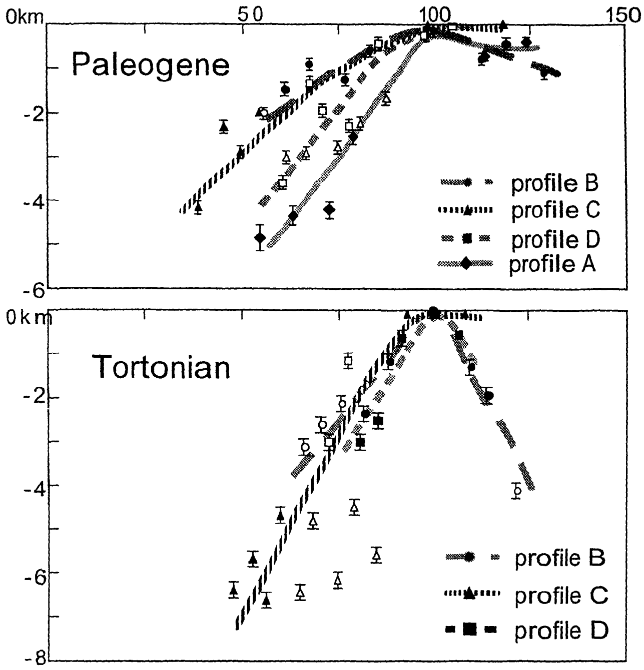

Figure 6. Plots of the base foredeep positions along the sections of Figure 3 for the Late Paleogene and for the Tortonian. The base foredeep profiles have been shifted in order to let the bulges coincide and thereby facilitate the comparison among the profiles. Solid and open symbols show well-cosntrained and less well-constrained thicknesses, respectively. In the bottom graph, profile A has been neglected because of its anomalous behavior.

where the Paleogene is <100 m thick and from where a sedimentary wedge opens toward the north [*Pieri and Groppi*, 1981].

The width of the basin in the N-S direction is only poorly controlled because it is not known how far to the south the thrust belt had arrived. In map view, however, the trace of the Paleogene bulge shows an embayment toward the south. Assuming a linear strike of the fold-and-thrust belt, this would imply a wider basin in the central part of the studied area and would be compatible with the higher strength reconstructed for this lithospheric segment.

Systematic lateral variations are further observed in the vertical elevation of the bulge which was below sea level in the central parts but emerged above water on the sides [*Dondi and D'Andrea*, 1986]. This pattern again suggests a stronger lithosphere in the central domains.

The position of the Late Paleogene lithospheric bulge [*Pieri and Groppi*, 1981] shows striking correlations with the location of highs inherited from Mesozoic rifting. In profile B, the bulge is located in correspondence to an important Mesozoic high on which the entire Mesozoic succession is represented by 460 m, and the Jurassic and Cretaceous are represented by only 80 m (Battuda 1 well). A somewhat similar situation is found in profile C where the Paleogene bulge is located in an area with reduced or no sedimentation from the Cretaceous to the late Miocene as shown by the Valle Salimbene 1 well (Figure 3). Also profile D shows a very similar situation with the bulge being located in an area where the Cretaceous section is only few tens of meters thick (well Rodigo 1). It seems therefore that the old highs are important in controlling the position of the bulges (sites of minimum sedimentation) throughout the foredeep evolution. This is, however, the case only if the high is not far away from the theoretical position of the bulge, that is not too close to the front of the thrust belt. The Mesozoic Malossa high [*Errico et al.*, 1980], for instance, was brought at greater depths and buried beneath thick younger sediments during the Tertiary (Figure 3).

3.2. The Late Tortonian

Profiles through the foredeep in the Tortonian (Figures 6 and 7) show an increase in basin depth up to more than 6000 m. With the only exception of profile A, which will be discussed below, the profiles show a clear steepening of the base foredeep with respect to the Late Paleogene configuration (Figure 7 and Table 1). Dip angles reach values up to 8°, describing thereby a very steep position of the basin bottom. In a mechanical perspective, the increase in dip occurring between the Late Paleogene and the Tortonian implies an increase in curvature which is associated with a strength reduction of the flexed lithosphere. A comparison of the values reconstructed for the various profiles (Figure 6) shows that the differences in dip angle among the profiles which was clear in the late Paleogene was reduced by Tortonian times. This implies that the mechanical inheritance which still influenced the Late Paleogene configuration was progressively overshadowed by the weakening of the flexed lithosphere related to the foreland basin formation.

Profile A has an anomalous behavior in that it shows a drastic deepening of the entire base foredeep from the Late Paleogene to the Tortonian. This affected not only the deeper parts of the basin but also the lithospheric bulge which subsided by some 2000 m during the considered time frame. During this downward movement, the dip of the base foredeep remained roughly constant. The anomalous behavior of profile A is possibly related to the close proximity of the South Alpine and Apenninic fronts in pre-Messinian times which caused a "collapse" of the intervening basin ("yoking" of *Quinlan and Beaumont* [1984], and *Moretti and Royden* [1988]). Similar geometries have been described from analog experiments by *Cobbold et al.* [1993].

Available seismic profiles [*Pieri and Groppi*, 1981] allow a good definition of the bulge position during the Miocene. As a rule, it coincides with the site of Paleogene minimum sedimentation. Along profile A, it corresponds to the Ottabiano 1 - Mortara wells. Sedimentary thickness relationships are very clear along profiles B and, even more, along C. In the Battuda 1 well, only <500 m of Lower to Middle Miocene sediments are found which contrast with the >1.5 km thick successions found farther to the north and to the south. In the Valle Salimbene 1 well (Figure 3), the Upper Miocene is lying directly on top of Mesozoic rocks, and no Lower to Middle Miocene is recorded. A similar, although less striking, situation is found along profile D where the site of minimum sedimentation is located around the Rodigo 1 well where Lower to Middle Miocene sediments are < 50 m thick.

These observations show that, despite the progressively more southerly position of the chain, the site of minimum

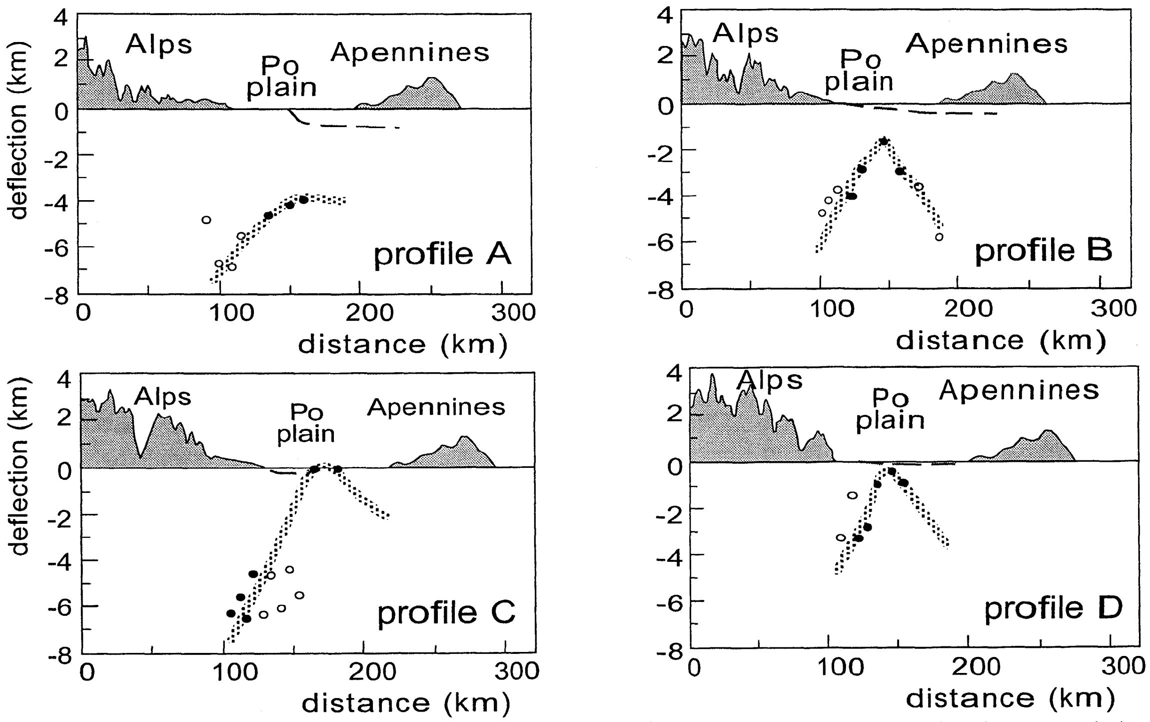

Figure 7. Base foredeep at the Tortonian along the four profiles shown in Figure 4. Solid and open symbols show well-constrained and less well-constrained thicknesses, respectively. The dashed lines give the paleobathymetric profiles adopted [from *Bernoulli et al.* [1987], *Gelati et al.* [1988, 1991], *Dalla et al.* [1992], and *Barbieri* (unpublished data, 1995)). The mountains shown in the graphs are meant only as geographic reference to the present-day situation. Note how in the southern part of the profiles, the base foredeep dips to the south as a consequence of loading by the Apennines.

sedimentation on the Adriatic plate remained unchanged from the Paleogene to the Late Miocene. In other words, the lower plate remained stationary with respect to the site of minimum sedimentation. This is in contrast with what is considered to happen in "normal" situations where the subducting plate moves through the bulge [*DeCelles and Giles*, 1996].

4. Tracing the Weakening of the Loaded Plate

The analysis of seismic- and well-derived data has demonstrated that the loaded plate was progressively flexed around a stationary domain, the foredeep bulge. An increase in dip requires an increase in the curvature of the hinge zone. During this process, stresses are generated in the external and internal parts of the flexed plate which will overcome the strength of parts of the plate and cause its weakening [*e.g.*, *Burov and Diament*, 1992].

In order to quantify the weakening suffered by the loaded plate, we estimate the elastic thickness of the lithosphere before the onset of loading (Late Cretaceous), at an intermediate stage (Late Paleogene), and at the end of foredeep formation (Tortonian). The mechanic configuration before the initiation of the foredeep will be derived by extrapolating to the Po Plain subsurface of the results obtained by *Bertotti et al.* [1997] for the exposed transect of the South Alpine margin. Strength

Table 1. Dip of the Base Foredeep, Radii of Curvature of the Hinge Zone, and Derived *Te* Values for the Considered Profiles Across the South Alpine Foredeep in the Late Paleogene and in the Tortonian

	Cretaceous	Late Paleogene			Tortonian		
	Te [1], km	Dip, deg	Radius, km	*Te* [2], km	Dip, deg	Radius, km	*Te* [2], km
profile A	?	7.1	?	?	3.5	?	?
profile B	27	2.8	190	15-20	5.6	85	< 5
profile C	?	3.5	?	?	6.7	?	?
profile D	25	5.5	200	15-20	7.8	90	< 5

[1] Values derived from the rheological configuration after breakup.
[2] Values are obtained on the basis of the curvature of the Adriatic plate

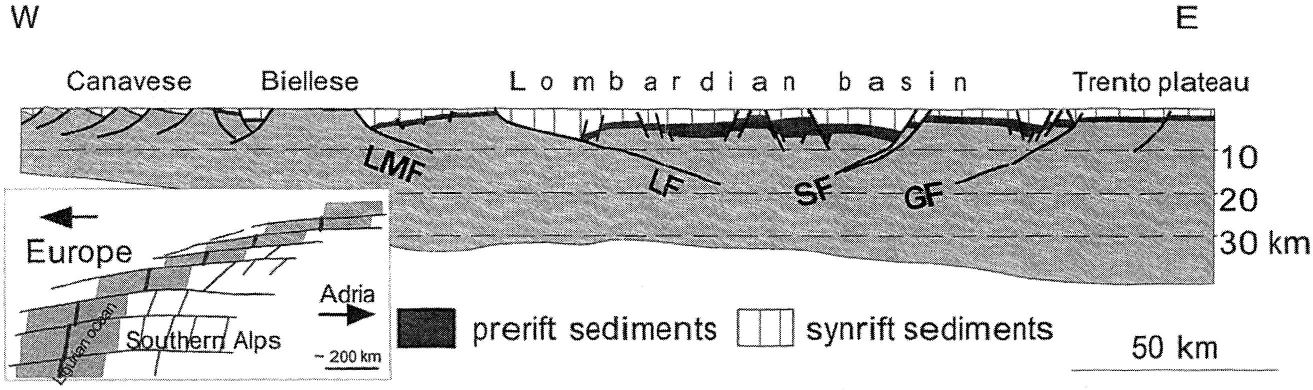

Figure 8. Crustal profile across the South Alpine passive continental margin at the onset of Adria-Africa convergence. Figure 8 has been constructed extrapolating at depth the fault geometries and displacements observed in the upper crust. In order to take into account the Variscan thickening, an initial crustal thickness of 40 km has been assumed (from *Bertotti et al.,* 1997]). Abbreviations are as follows: LMF, Lago Maggiore fault; LF, Lugano fault; SF, Sebino fault; and GF, Garda fault. Inset shows the plate tectonic configuration during the Middle Jurassic [from *Weissert and Bernoulli,* 1985].
Reprinted from Earth and Planet. Sc. Lett., 146, Bertotti, G., M. ter Voorde, S. Cloetingh, and V. Picotti, Thermomechanical evolution of the South Alpine rifted margin (North Italy): Constraints on the strength of passive continental margins, 181-193, 1997 with kind permission of Elsevier Science-NL, Sara Burghartstraat 25, 1055 KV Amsterdam, The Netherlands.

estimates during and at the end of foredeep basin formation are derived in a different way, namely, by analyzing the curvature of the flexed plate and translating it into *Te* values; for this purpose, we follow procedures developed by *Burov and Diament* [1995].

4.1. Tectonicmechanic Configuration Prior to the Onset of Convergence

4.1.1. The South Alpine transect. The Southern Alps and adjacent regions underwent continental rifting from Late Triassic to Middle Jurassic times followed by the drifting apart of the European and Adriatic plates (Figure 8) [*Laubscher and Bernoulli,* 1977]. Extensional kinematics and subsidence patterns in the Southern Alps are fairly well known [*Bertotti et al.,* 1993]. Rifting began in the Late Norian and until the Toarcian was mainly localized in the central parts of the Southern Alps where the Lombardian basin formed (Figure 8). This basin was limited to the east by two west dipping faults, the Garda and Sebino faults, and to the west by the east dipping Lago Maggiore and Lugano faults. In the Toarcian, extension in the Lombardian basin gradually ceased and shifted westward where it eventually led to Middle Jurassic continental break up. Drifting followed and ended in the Late Cretaceous with the onset of convergence between Adria and Europe.

Thermal-rheological modeling of the South Alpine passive margin along an E-W section through the Southern Alps has provided predictions for the thermal evolution of the margin and estimates for the lithospheric strength at various stages [*Bertotti et al.,* 1997]. This study has shown that 100 Myr after breakup, that is, roughly at the onset of convergence, modeled *Te* values ranged from 27 km in the Lombardian basin to ~ 23 km on its sides. Higher *Te* values are, indeed, expected in extended lithospheric segments when the isotherms have fully recovered from any previous rifting-related perturbation. The strength of the lithosphere is then controlled by the relative thickness of the lithological layers (upper and lower crust and mantle) [*e.g., Vink et al.,* 1984].

4.1.2. Po Plain subsurface. To reconstruct the strength of the South Alpine lithosphere immediately before loading, we first correlate extensional structures in the Po Plain subsurface with those exposed at the surface. We then extrapolate the strength and *Te* values determined in the Southern Alps to the Po Plain basement.

Only an incomplete record of extensional structures can be derived from the Po Plain subsurface (Figure 9). However, seismic profiles [*Pieri and Groppi,* 1981] clearly show two west dipping normal fault systems lying on the southward continuation of the Sebino and Garda faults (Figure 9). The prolongation of the Garda fault forms the western boundary of the Rodigo high [*Pieri and Groppi,* 1981]. This has a stratigraphic succession very similar to those of the Trento Plateau with a thick Norian to Liassic carbonate platform unconformably overlain by a few tens of meters of Cretaceous to Miocene rocks. In the west, an east dipping normal fault is clearly visible delimiting the Turbigo high [*Pieri and Groppi,* 1981] and lying on the southward prolongation of the Lago Maggiore fault. The Turbigo high is characterized by thin and discontinuous Triassic covered by middle Jurassic pelagics. Both the Rodigo and Turbigo highs are long-lived structural and morphological features. The overall fault pattern of the Po Plain subsurface mimics structures in the exposed part of the orogen with two sets of inward dipping normal faults bounding the central, most extended area, the Lombardian basin. The faults seem to terminate toward the south against an E-W trending structure which is inferred from the jump in depth of the magnetic basement, from the abrupt thickness variation of the Mesozoic sediments [*Cassano et al.,* 1990], and the dramatic change in thrusting imbrication geometry. Given the dominant

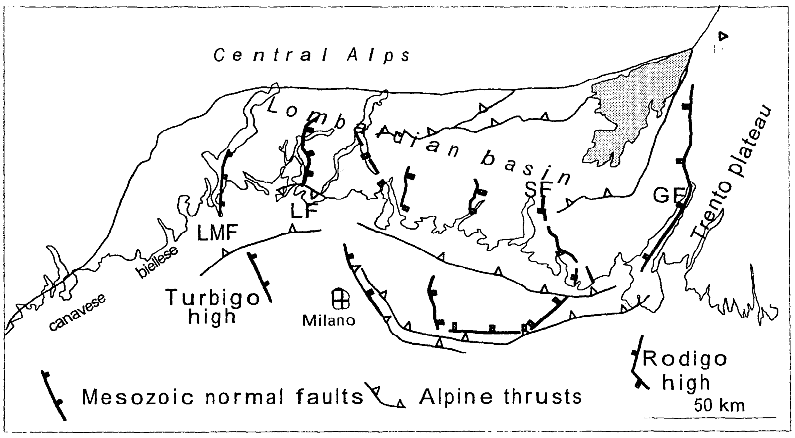

Figure 9. Main Mesozoic structural features of the Po Plain subsurface (from *Pieri and Groppi* [1981] and our own data)

Mesozoic E-W direction of extension recorded in the Southern Alps, this E-W trending structure should have a mainly transfer character. The termination of the extensional basins against roughly E-W trending lineaments is fairly well known from the exposed chain [*e.g., Kälin and Trümpy*, 1977; *Castellarin and Picotti*, 1990].

The amount of extension accommodated along the faults described in the Po Plain subsurface cannot be determined directly from available profiles. In order to preserve kinematic compatibility with the section exposed in the Southern Alps, we assume that the same stretching factors affected the corresponding domains of the two areas. The lack of evidence suggesting differences in the thermal history of the two domains during Jurassic to Late Cretaceous time allows us to adopt the same *Te* values for regions which underwent similar tectonic histories (Figure 10). The resulting map shows *Te* values of >27 km in the Lombardian basin and its southern continuation as well as for the westernmost areas. These thinned and relatively strong areas are surrounded by domains of intermediate strength (*Te* values between 25 and 27.5 km) and eventually by the less thinned and therefore weakest zones (*Te* < 25 km).

4.2. Geometric and Mechanical Changes During Foredeep Basin Formation

Modeling procedures developed by *Burov and Diament* [1995] and earlier workers allow the derivation of semiquantitative estimates of the strength (effective elastic thickness) of the flexed lithosphere during foredeep basin formation on the basis of curvature. The analysis of the curvature of the Adriatic plate is significant also because of the presence of a southward thickening sedimentary wedge associated with the Apennines fold-and-thrust belt south of the South Alpine foredeep (Figures 1 and 2). The Northern Apennines developed beginning from Late Eocene times and presently form three major arcs in the Po Plain subsurface [*Pieri and Groppi*, 1981; *Castellarin et al.*, 1985] which become

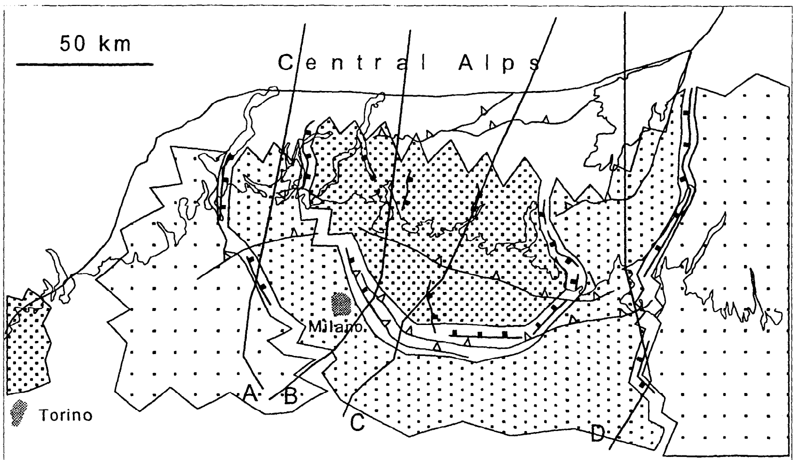

Figure 10. Effective elastic thickness (*Te*) values in the northern Adriatic plate in the Late Cretaceous at the onset of convergence. The main tectonic subdivisions are constrained by seismic and well data. The *Te* values are extrapolated from the passive margin section exposed in the Southern Alps (see text).

younger from west to east. A well-developed foredeep formed in front of the advancing thrust sheets [*Ricci Lucchi*, 1986] partly interfering in space and time with the formation of the South Alpine foredeep. As a result of double loading, the lithosphere underlying the Po Plain was progressively flexed and presently dips in the north beneath the Southern-Alps and in the south beneath the Apennines [*Cassano et al.*, 1990; *Giese et al.*, 1992].

We have measured the Late Paleogene and Tortonian curvatures of the Adriatic plate (thus including also the Tortonian Apenninic bulge) along two well-suited, roughly N-S trending profiles: one (profile B) crosses the Mesozoic Lombardian basin, the second one (profile D) lies farther to the east in a less extended area. Curvature estimates have been obtained by determining the radius of the circle passing through three selected points of a profile and therefore are not dependent on any "modeling" assumption. Different triplets provide slightly different curvatures and provide an estimate of the solidity of the results. Error margins calculated in this way are always <10 km thereby not substantially influencing the results. The translation into *Te* values, as proposed by *Burov and Diament* [1995], is based on the correlation between the stresses generated by flexing a plate and the thicknesses of the plate which will fail as a consequence of those stresses. Note how only numerical experiments assuming a fully decoupled state for the lithosphere are able to fit the observed curvature values.

The radii of curvature estimated for the two Late Paleogene profiles are of 200±20 km (Table 1). The corresponding *Te* values are in the 15-20 km range. These values are lower than those derived from modeling the precontractional configuration. On the contrary, no significant difference is observed between the two profiles despite their different position with respect to older, rift-related structures. The two profiles did show different base foredeep dips, but the translation in *Te* values does not resolve the difference. Radii of curvature in the Tortonian, at the end of foredeep basin evolution, are of 90±10 km (Table 1) and are therefore substantially lower than those derived for the Late Paleogene. *Te* values obtained for these curvatures are <5 km and cannot be further resolved. All uncertainties taken into account, these results clearly demonstrate the weakening undergone by the loaded plate.

It is important to repeat that the weakening mentioned above affected a segment of the loaded plate, the bulge, which did not change through time. We have demonstrated in section 3 that the South Alpine bulge remained stationary through time with respect to the loaded plate (see also Figure 3). The progressive weakening monitored by the increase in curvature, affected always the same lithospheric segment and not always new domains introduced into the system.

5. Discussion

One of the most significant results of this study is that the Adriatic plate is inferred to have undergone drastic reduction of lithospheric strength during loading and flexing related to convergence. In the following, we want to discuss possible processes which could have led to the observed changes. Possible candidates are 1) the southward movement of the Alpine belt, 2) the filling of preexisting paleobathymetry, 3) modifications of the deep loads, and 4) interactions between the upper and lower plate of the Alpine subduction system.

The southward movement of the Alpine belt is not able, in itself, to explain the observed dip increase and concomitant plate weakening. In a simple situation, a steady state configuration is achieved for the geometry of the flexed lithosphere. Provided that the parameters of the system such as load and *Te* remain the same, then the shape of the foreland basin (for instance, the distance between the applied load and the hinge zone of the lower plate, Δx in Figure 11) also remains constant through time. With proceeding subduction, new segments of the lower plate are always introduced into the system and therefore enter, pass and exit the hinge zone. In this sequence, new lithospheric segments always undergo some weakening which is, however, limited by the fact that these segments eventually escape the deformation zone. This is not what we observed for the South Alpine foredeep, the geometry of which changed through time.

Changes in the deep loads. To explain the depth increase, one could invoke changes in the loads applied to the lower part of the subduction system. In some cases, modelers were compelled to envisage "hidden loads" in order to fit the observed plate flexure. The nature of these "hidden loads" is still a matter of speculation, and, in the absence of further constrains, we prefer not to invoke explanations which at the moment cannot be geologically tested.

Filling of pre-existing paleo-bathymetry. In the South Alpine foredeep, Late Paleogene paleowater depths are larger than Tortonian ones (Figures 5 and 7). Replacing water with sediments obviously increases the load acting on the flexed plate. To estimate the effects of this processes, we have carried out numerical experiments analyzing the subsidence caused by applying an extra load to a thin plate. Thicknesses of the applied extra load are derived from the profiles of Figures 5 and 7. In the range of adopted *Te* values (20-10 km) and sediment densities (2300 - 2450 kg/m^3), the experiments show that extra-subsidence is roughly of the same order as magnitude of the height of the water column which is replaced by sediments. In the profiles where thicknesses and water depths are well constrained, such as for profile C, the subsidence caused by the water-replacement effect corresponds to roughly 50% of the total observed Late Paleogene to Tortonian subsidence. Our numerical experiments demonstrate therefore that filling of preexisting paleobathymetry is an important cause for the increase in base foredeep dip, but it is, in itself, not able to justify the total observed subsidence.

Interactions between upper and lower plate. Our interpretation of the data relies much more on the observation that the Alpine convergence system is controlled by the subduction of the European plate [*Bernoulli et al.*, 1990; *Pfiffner*, 1992] and that the South Alpine foredeep developed on the upper plate (retroforeland basin). In one respect, at least, the evolution of these basins differs substantially from the one of proforeland basins, namely, in the intuition that upper plates are not efficiently subducted. As a consequence, the hinge zone (bulge) of the initial stages will remain such during basin evolution. If the flexed part of the lithosphere cannot escape from the hinge zone, a feedback process is started with deformation being localized around weak segments, these

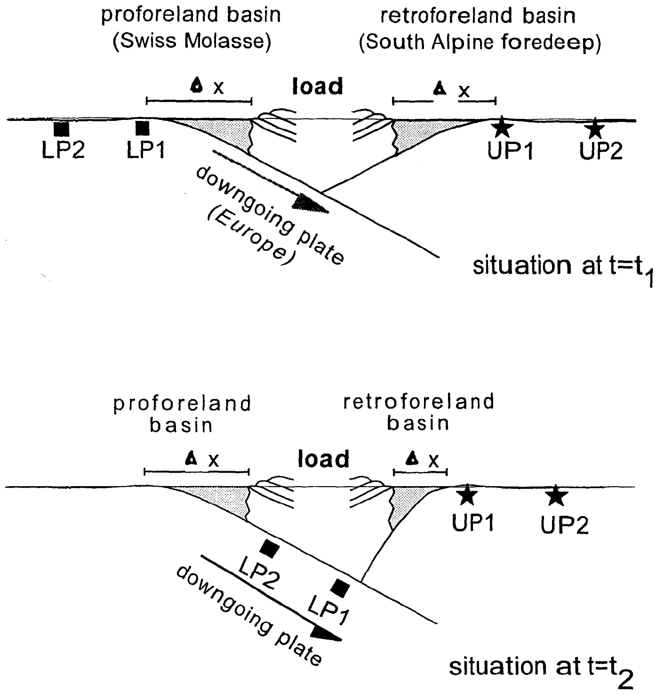

Figure 11. Illustration of the different evolution of foreland basins developed on subducting and on overriding plate segments (proforeland and retroforeland basins, respectively). In the Po Plain system, time t_1 would correspond to the Late Paleogene, and t_2 would correspond to the Tortonian (see text for discussion). Lower plate material points (solid squares) pass through the system, and weakening always affects new lithospheric segments. Lower plate points (stars), on the contrary, tend to remain stationary: weakening therefore tends to remain localized around the same point (UP1 in Figure 11).

becoming weaker because of increasing folding and thereby causing further localization of the deformation. The process is also favored by the increasing degree of continental collision which caused an increase of the horizontal stresses applied to the Adriatic lithosphere and by other processes related to the complex upper plate/lower plate dynamic interactions [*e.g., Mitrovica et al.,* 1989]. The result is a dramatic reduction of the lithospheric strength through time. In the last evolutionary stages, the hinge zone of the Adriatic lithosphere was approaching a no-strength configuration. A similar weakening in time has been recently assumed by *Toth et al.* [1996] for the Subandean foredeep of NW Argentina which, similar to South Alpine foredeep, is a retroforeland basin.

The close connection between the evolution of the bulge and its position with respect to the subduction system is clearly demonstrated by the difference in evolution between the South Alpine and the Apenninic bulges. We have demonstrated that the South Alpine bulge, an "upper plate" bulge with respect to Alpine subduction, remained stationary through time. The same area, however, is a "lower plate bulge" for the Apennines fold-and-thrust belt since it is located on the plate being subducted beneath the Apennines (Figure 2). The position of the bulge changed in time, and the Apenninic foredeep progressively incorporated older bulge areas (see, for instance, the interpreted seismic profile of Figure 3).

The curvatures observed for the South Alpine foredeep, especially in its last evolutionary stages, are very high (very small radii). As already noticed by *Burov and Diament* [1995], this strongly suggests a decoupling between the upper/middle crust and the upper mantle. Model calculations of the same authors show that a lithosphere with efficient coupling between upper crust and upper mantle cannot sustain curvatures with radii <400 km [*Burov and Diament,* 1995]. The most likely candidate as decoupling horizon is the lower crust where rocks have very low yield strengths. We have therefore compared the curvatures we have measured with the one given by the Moho beneath the Po Plain [*Schmid et al.*, 1996]. The Moho radius of curvature turns out to be of about 140-150 km, which is substantially higher that what is observed for the base foredeep. This difference supports the notion of a decoupling between upper/middle crust and upper mantle, with lower crustal rocks "flowing" toward the hinge zone. Temperatures at Moho depths beneath the Po Plain are considered to be in excess of 700°C [*Cermak and Bodri*, 1995] and therefore are clearly high enough to allow for efficient flow at lower crustal levels.

6. Conclusions

The results of this study underlie the importance of the temporal and spatial changes of properties which affect a lithospheric segment during loading and folding as a consequence of shortening and continental collision. The configuration of the South Alpine passive margin before contraction was such that some 100 Myr after breakup the segments with most thinning were the strongest. Lateral strength distribution influenced the geometry of the foreland basin during its initial stages. The parts of the foredeep which formed on the stronger domains of the loaded plate have a shallow-dipping base and low bulges. Parts of the foredeep developed on weak segments have steeper bases and higher bulge elevations. With proceeding shortening and loading by the South Alpine and Apenninic belts and given the upper plate position of the Adriatic plate which prevented a rejuvenation of the bulge, the hinge focused more and more deformation by becoming weaker and weaker. Already during the last stages of evolution, the mechanical characteristics inherited from the extensional phase had been obliterated, and the geometry of the basin was mainly controlled by the changes occurring during foreland basin formation.

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